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Review of Static Seals for Cryogenic Systems

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Although cryogenic techniques have advanced rapidly, little effort has been devoted to standardization of seals for cryogenic systems. This paper surveys and evaluates various demountable, low-temperature static seals. Rectangular-sectioned gaskets of Teflon or Kel-F, or of soft metal, or with plastic sealing surfaces can be used, but gaskets require heavy flanges. O-rings of rubber, Viton, and neoprene have been used successfully down to 20° K with high-initial-loading designs. Hollow, metallic O-rings can be used, but they are hard and require good surface finishes, $\geq$16 rms. Solid O-rings of soft metals (e.g., indium, lead, copper, and aluminum) can seal to 10^{-5} atm-cc/sec/linear-in. Pressure-actuated seals of C, U, V, or W configuration are said to be superior to all others for cryogenic space systems (a table of available types is given); they use lightweight flanges and will follow flange deflections; they are expensive, and small leak paths can develop, but they have proved reliable in the field. Temperature-actuated seals (favorable thermal contraction relationships) also show promise but have not been used extensively.

AUTHOR:

Introduction

During the past decade, although cryogenic propellant techniques have advanced at great speed, little thought has been given to standardizations of demountable low-temperature static seals. The lack of a comprehensive experimental evaluation of the countless varieties of seals available (each of which claims superiority over rival designs) prompted this paper, which reviews cryogenic static seals as they are available today. It does not include descriptions of dynamic seals, welded or brazed joints, moving-valve seals, sealant materials, or highly specialized designs. It is based on a literature survey, personal contacts with those working with cryogenic systems, and National Bureau of Standards research experience (particularly for the elastomer O-ring section). Inevitably, many excellent sources of information have been neglected; hopefully those agencies will understand the difficulties resulting in our not discussing cryogenic sealing with all of them.

Seals are separated into four arbitrary categories depending on seal cross section or sealing principle to define each category. Basic designs are presented, along with a discussion of leakage magnitudes, oxygen compatibility, flange design, and other critical parameters.

Gasket Seals

The distinction between an O-ring seal and a gasket seal is rather arbitrary. A gasket will be defined here as any seal that has a rectangular cross section, with the seal width somewhat larger than the gasket thickness before compression.

Before World War II gaskets were universally used for demountable seal applications. In cases where weight is unimportant, gaskets are still the logical solution to the cryogenic seal problem. Standard flanges are available for some gasket systems, and these simplify seal design.[1, 2] However, the thermal effects involved and the volatile nature of some cryogenic fluids are problems that do not exist in "standard" applications. Therefore, gasket materials are selected for their ability to withstand the temperature reduction without becoming brittle and for their chemical inertness. Flanges and bolts are chosen so that cooling will not cause an increase in the space between flanges, resulting in seal failure. The following gaskets are representative of those being used in cryogenic hardware, with main emphasis on missile-system ground-support equipment and high-vacuum equipment.

Gaskets Made from Soft Plastics

For service in oxygen environments, most elastomeric materials are eliminated immediately, and tetrafluoroethylene (Teflon)† has become a top candidate for gasket fabrication.[3, 4] Other plastics such as chlorotrifluoroethylene (Kel-F)‡ can be used in the designs described, but Teflon is the most widely used at present, and we will refer only to Teflon,[5] which can be cut from sheet or from tubing. Teflon has the undesirable property that it will flow under an applied force, reducing the sealing force and causing leaks.[3] Four methods for reducing the flow problem are sketched in Fig. 1.

Sketch 1a shows a gasket cross section in which Teflon has been filled with particles or fibers (usually glass), which add strength, reduce thermal contraction, and inhibit cold flow. Such gaskets are quite hard and require higher flange loads and more exact flange surface finishes than unfilled gaskets. Methods of compounding and mixing are important, and orientation of the fibers plays a part in the thermal expansion. Knowledge of these factors, as well as proper flange design, is necessary if a reliable seal is to result.

Asbestos fibers mixed with a suitable binder and formed into sheets have been widely used as gasket materials for high-temperature applications.[3] The fibers retain a certain amount of resilience, a desirable property inherent in elastomeric gaskets but lacking in solid-metal or plastic gaskets. For cryogenic service Teflon is used as the binder and sealing surface as shown in Fig. 1b. The Teflon reduces the resilience of the asbestos somewhat, but this combination has more resilience than glass-filled Teflon, and many versions have been produced which are compatible with LOX. A disadvantage is that the Teflon tends to flake away from the edges of the gasket. This problem can be solved by stamping copper ferrules to the inner and outer surfaces and by designing the flanges so that the ferrules are not part of the sealing surfaces.

Sketch 1c shows a method for combining the resilience of the asbestos felt with the sealing properties of Teflon. The

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† ® Trademark: E. I. du Pont de Nemours and Co. (Teflon).
‡ ® Trademark: Minnesota Mining & Manufacturing Co. (Kel-F).

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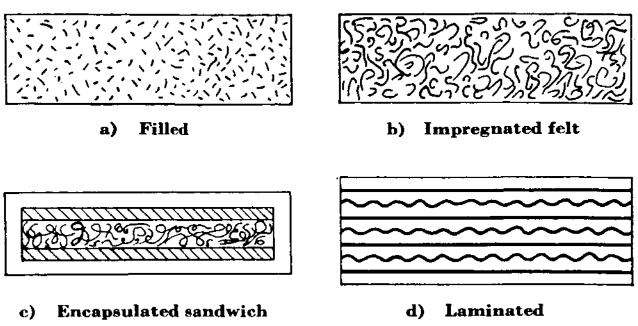


a) Filled b) Impregnated felt c) Encapsulated sandwich d) Laminated

Fig. 1 Tetrafluoroethylene gasket composites.

felt body is sandwiched between two metal disks that provide a smooth surface and give added mechanical rigidity in the radial and circumferential directions. The sandwich is encapsulated in Teflon to provide a soft LOX-compatible sealing surface.

A recent innovation that may have promise is the laminated gasket (Fig. 1d). Alternate layers of a reinforcing material such as glass cloth and a binder such as Teflon are formed under compression to result in a gasket that does not flow, has a soft sealing surface, and does not become appreciably harder when cooled to cryogenic temperatures.[6] If the laminate edges show a tendency to shed or flake, the gasket can be encapsulated in Teflon or another suitable material. Future research should provide justification for commercial production of laminated gaskets for cryogenic service.

Several companies report that the forementioned gasket concepts will provide "zero leak" seals for cryogenic service. In most cases zero leak is defined here as 0.1–3.0 atm-cc/sec/linear-in. of seal, which is acceptable for LOX transfer systems in ground-support equipment but not for high-vacuum service. The general concensus on flange design seems to be that standard ASA raised-face flanges with concentric serrations over the entire sealing surface provide the most reliable sealing surfaces. Other information concerning soft plastics is found in Refs. 7–11.

Gaskets Made from Soft Metals and Hard Plastics

The softer metals, such as copper and aluminum, and the hard thermoplastic polymers, such as Mylar,§ are used in a similar manner, and they will be treated together. In order to achieve a "leak-tight" seal, high-stress concentrations must be applied to these materials. Consequently, flanges are designed to apply high stresses to small concentric sections of the gasket. These sections are wholly responsible for the success or failure of the seal. Precautions must be taken to avoid overcompression of the seal material, and radial scratches on the sealing surfaces must be carefully avoided. Gasket materials in this group do not have the ability to follow any flange movement in the axial direction; hence, precautions must be taken to avoid such deflections. Figure 2 shows some methods of achieving excellent seals with this class of gaskets which have often been used in high-vacuum applications.

Mylar has been particularly useful with the design shown in Fig. 2a which has been used in high-vacuum, low-temperature applications.[12–14] A ring with a $\frac{3}{16}$-in. radius of curvature is machined so that the maximum height is 80% of the gasket thickness. Ten-mil Mylar has been used successfully, although optimization of the gasket thickness has been only partially investigated.[14] Mylar has the disadvantage of being LOX-impact sensitive.

Many varieties of the knife-edge seal shown in Fig. 2b have been used successfully in high-vacuum work.[15–18] Annealed copper or aluminum gaskets about $\frac{1}{16}$-in. thick are satisfactory, with the raised V-rings machined so that the height is 60–70% of the gasket thickness.[17] In this design the surface finish of the raised rings is quite important, and small scratches can cause leakage. Vacuum grease applied to the gasket will help eliminate leaks caused by minute scratches when a high-vacuum seal is required.

The designs shown in Figs. 2c and 2d are generally used with aluminum foil or other thin sheets of soft metals.[19–21] In Fig 2c the shearing action of the step is primarily responsible for sealing action, and a fusion between gasket and flanges often results. Extremely close machining tolerances are required. When the step is machined at an angle of more than 90°, a cone shape results, and this modification is common when thin films are used. Sketch 2d could easily fit into the O-ring classification, since a solid-metal ring acts to apply high compressions to the sealing surfaces. The gaskets are usually aluminum foil. Flange surface finish is again a critical factor.[22–24]

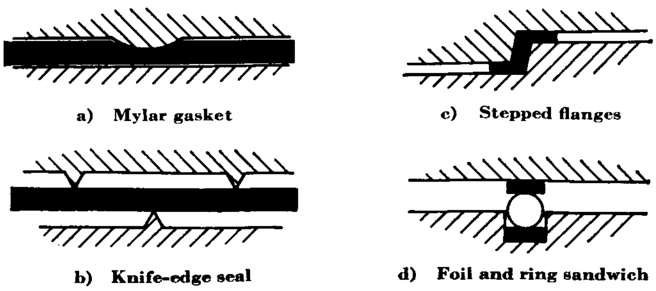
Composite metal gaskets made by combining a mesh skeleton of a hard metal with a soft-metal filler show some promise for low-temperature seals, although they are being developed for high-temperature applications. The most promising materials are babbit and indium fillers with molybdenum and stainless-steel skeletons.[25, 26]

Hard-Metal Gaskets and Spiral-Wound Gaskets

When a metal is used as a gasketing material with flanges of a similar hardness, great care must be taken to avoid scoring the flanges, and high-point loading must be present to insure satisfactory performance.[27, 28] This combination of requirements makes the metal-to-metal type of gasket seal quite difficult to design; however, one commercial gasket-flange combination has met with some success and is being used by several companies (Fig. 3a). The gasket is designed so that high loads develop along the inner and outer edges during the last stage of compression. At this stage the flange faces, which are machined to accept the conical gasket, meet the main gasket surface and thereby prevent bowing of the gasket. Great care must be taken to insure uniform loading of the gasket and very clean, uniform surfaces at the contact edges. This gasket configuration will produce good seals only if such care is taken.

The contact surface of an all-metal gasket may also be reduced by producing the gasket in cross sections, such as the profile and serrated types[3] (Fig. 3b and 3c). These gaskets are made from many metals, with soft steel a commonly used material. Obviously, the gasket metal must be at least as soft as the flange metal. No information is available concerning the success of these seals at low temperatures; however, if the metals are chosen with temperature activation at low temperatures in mind, they show some advantages due to LOX-compatibility considerations and simplified flange design.

The last gasket to be described combines the spring-like properties of a U-, V-, or M-shaped metal ring with a sealing surface of asbestos or polytetrafluoroethylene, as shown in Fig. 3d. The crimped metal is wound spirally, alternating layers with the filler material. These gaskets behave in a spring-like manner and have been used in high-pressure, high-



a) Mylar gasket c) Stepped flanges b) Knife-edge seal d) Foil and ring sandwich

Fig. 2 Soft-metal and hard-polymer seal designs.

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temperature applications for 50 years. Some success has been noted at cryogenic temperatures, but high loading and scoring of flange faces are disadvantages.

Summary of Gaskets

The following brief statements reflect the general impressions of gaskets for cryogenic service: 1) Gaskets require rigid, heavy flanges, which may not be suitable for airborne applications; 2) soft-metal gaskets can be used for high-vacuum seals; 3) new techniques for incorporating a soft plastic sealing surface in gaskets look promising; and 4) hard-metal gaskets could probably be used with liquid oxygen and in bakeable systems.

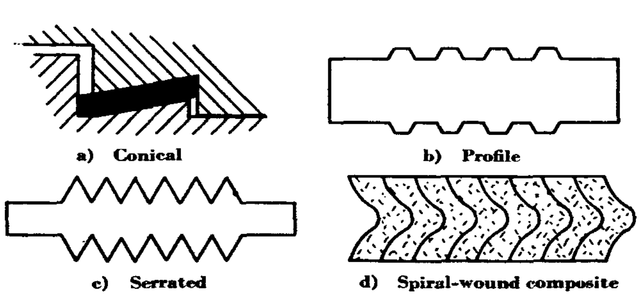
O-Ring Seals

O-ring seals became accepted only 20 years ago, when aircraft development required versatile, reliable, lightweight seals for hydraulic systems. Their development has been rapid, and some types have been used at low temperatures. In this section the more common materials and designs, as they apply to the environments of cryogenics, will be treated.

Elastomeric O-rings

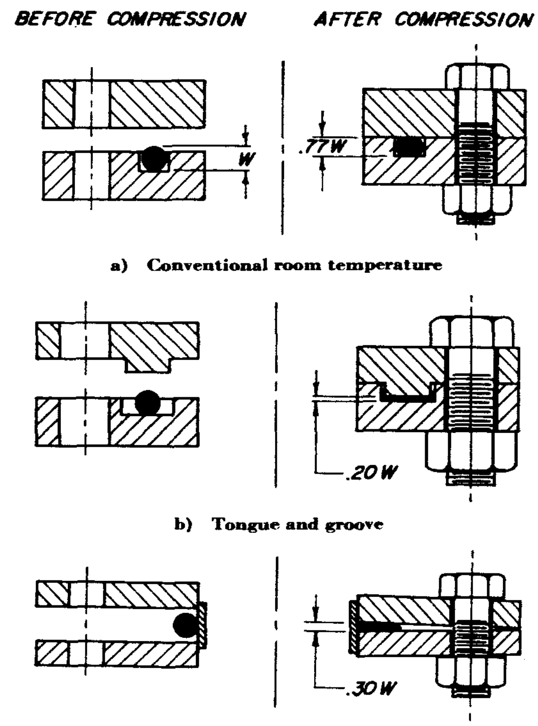
The simplicity, reliability, and long service life of the rubber O-ring have led to uses ranging from miniature seals in waterproof watches and fountain pens to large seals in earth-moving equipment and diesel locomotives. In general, their uses are limited to a relatively narrow temperature region in which the O-ring does behave in a rubbery manner and in the sealing of fluids that will not react chemically with the seal material.[30] In recent years, however, research people have made significant advances that have expanded the useful temperature range, particularly in the areas of monomer synthesis and polymerization of fluoroelastomers and silicon elastomers, and some of these same materials are compatible with the fuels and oxidizers used in space efforts.[29] Unfortunately, the lower limit of the rubbery region is above the temperature range of operation of most cryogenic hardware; hence, seals designers have neglected elastomeric O-rings. This neglect was questioned by workers at NBS.[37]

The thought was that if the seal could be assembled at some temperature within the rubbery region, it would probably remain effective at low temperatures despite its brittleness. However, it was immediately obvious that standard designs would not work. Figure 4a shows a typical design, in which an O-ring is compressed in a groove with very low bolt loading. Below the glassy-state transition temperature the elastomer is hard and brittle, and the O-ring shrinks more than the grooved flange, causing leakage. A logical modification is to apply a higher initial force to the sealing surfaces, letting the O-ring deform freely (Fig. 4b). This results in three desirable effects. First, and most important, the higher initial force results in higher forces at the transition temperature, increasing the chances for a good cryogenic seal. Second, there is a decrease in thickness, minimizing the differential thermal contraction problem. Third, the seal



a) Conventional b) Profile c) Serrated d) Spiral-wound composite

Fig. 3 Hard-metal gaskets.



a) Conventional room temperature

b) Tongue and groove

c) Spring-loaded, lightweight

Fig. 4 Elastomeric O-ring designs.

width increases, lessening the chance for small leak passages to reach across the barrier. O-rings with W equal to $\frac{1}{8}$ and $\frac{1}{16}$ in. have been tested at NBS in the 1-in. nominal size. The tongue and groove should be dimensioned so that the flanges meet when the O-ring is one-fifth its initial thickness, including about 5% bulk compression.[37] High forces are required to accomplish this compression; therefore, heavy bolts and flanges are necessary. This brute-force technique is quite reliable, but the high bolt loads and heavy flanges limit its application.

A second modification designed to reduce bolt load and simplify this design is shown in Fig. 4c. The seal is spring-loaded by designing the flanges so that the O-ring is compressed to 0.3W when the outer edges of the flanges touch.[38] In this design care must be taken to insure against permanent set of the flanges and bowing between the bolt holes. Several materials, such as natural rubber, Viton,¶ and neoprene, made seals which leaked less than 10^{-4} atm-cc/sec/linear-in. in the temperature range 20°–300°K; the O-rings were $\frac{1}{16}$ in. thick and $2\frac{1}{2}$–3 in. in diameter, and the stainless-steel flanges were 0.2–0.3 in. thick.

Recent work, designed to reduce bolt loading without resorting to thin flanges, has incorporated thin films of indium on each side of the O-ring, with remarkable success.[39] The reduction in sealing force needed with rigid, more conventional flanges is apparently possible, because the indium film is ductile at low temperatures and will flow to follow any relative radial movements of the seal and flange surfaces. Compatibility with oxygen is a major stumbling block; of the elastomers currently available, only Viton has passed impact-sensitivity tests with LOX. Force relaxation is also a problem, which is met only by initial excess loading or retorquing of the bolts. At low temperatures, the O-ring materials are hard, and very little axial movement can be tolerated. Since the flange spring loading is important, a large part of the load is transmitted through the O-ring, and this is a further disadvantage. Despite these drawbacks, the elastomeric O-ring can solve many high-vacuum, low-temperature seal problems by a simple, inexpensive design.

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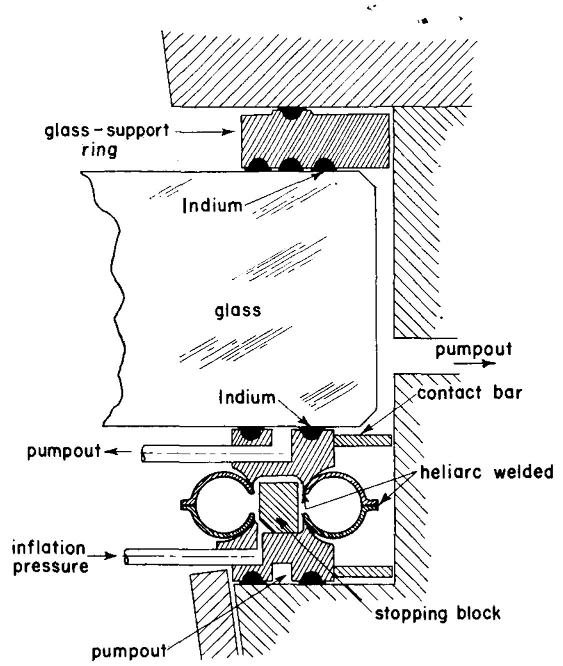


Fig. 5 Indium O-ring seal with inflatable bellows.

General information concerning permeability, outgassing, and radiation degradation, problems which are minimized in most cryogenic applications, can be found in Refs. 31–36.

Hard-Metal O-rings

Many brands of metal O-rings are available which can solve some of the problems experienced by elastomeric O-rings. Usually the metal structure of the O-ring is coated with a soft material, such as Teflon, lead, or silver, to provide a surface that will seal satisfactorily and yet resist the extreme environments just mentioned. Metal O-rings have a hollow, circular cross section or are solid with circular, oval, or hexagonal cross sections. The hollow O-rings enjoy wider use than the solid configurations due to the built-in spring effect. For high-pressure sealing, the hollow O-ring is vented to the pressure side by drilling small holes in the ring.[40] This enables the pressure-actuated principle (to be discussed in the next section) to be utilized, but the resultant increase in sealing force is much smaller than for seals specifically designed for pressure actuation. For this reason the vented hollow-metal O-ring appears to be inferior to the C, U, V, and W configurations (discussed later), when proper design and similar sealing surface coatings are used for each type. Many seals being used in the field have not been examined critically in the laboratory; hence the requirement for proper design is rather difficult to fulfill.

Solid-metal O-rings can be made from materials that match the flange and bolt materials, thereby eliminating the thermal expansion problems. However, the solid metals have high spring constants and thus will not follow flange deformations due to pressure pulses, nonuniform cooling, and vibration. In a recent seal-evaluation program, a solid hexagonal cross-section O-ring of 304 stainless steel with no surface coating was compared with a rubber O-ring tongue and groove design (Fig. 4b) and several other cryogenic seal concepts. Both the hex-ring and the elastomer O-ring gave satisfactory seal performance, but the hex-ring was recommended, since the tongue and groove design for the elastomer O-ring required close machining tolerances.

In conclusion, the following are advantages and disadvantages of metal O-rings. On the plus side, the metal is unaffected by environmental changes and is easily coated with a thin film of a reasonably good seal material. The hollow rings have some resilience and can be pressure actuated by drilling holes on the high-pressure side, but they are inferior to other shapes specifically designed for pressure actuation. In comparison with elastomers, the sealing surface has been compromised; it is harder, quite thin, and will not flow as readily into imperfections in the flange faces. Therefore surface finish must be quite good; 16 rms is a maximum roughness in most specifications, and small radial scratches incurred during assembly will cause leaks.

Soft-Metal O-ring Seals

Static seals made by compressing a ring of a soft metal, such as copper, indium, or lead, between flanges, find wide use in high-vacuum hardware, since the seal is often bakeable, can be cleaned, and is soft enough to fill minute imperfections in the flanges and to effect a seal which leaks less than 10^{-5} atm-cc/sec/linear-in. of seal. Such requirements cannot be met by either hard-metal or elastomeric O-rings.

For cryogenic service, indium is used extensively for glass-to-metal liquid hydrogen bubble-chamber window seals.[42–44] To maintain a constant seal pressure the bellows arrangement shown in Fig. 5 is used. As a precautionary measure a double seal is often used with a pumpout tap between the rings to vent any leakage to a safe external vacuum pump. Lead wire has also been used, but the difficulty in eliminating the carbonate coating has limited its use.[45] Copper and aluminum O-rings are less subject to cold flow and are used in a number of specialized ways, particularly in laboratory high-vacuum, low-temperature apparatus. Further information can be obtained from a number of papers,[46–51] which have been selected from a larger group.

Pressure-Actuated Seals

Just as aircraft technology around 1940 led to the elastomeric O-ring, the need for a new type of seal for the space age led to the pressure-actuated seal. To understand why this new, expensive seal is widely used today, one has only to understand that such seals must fulfill the following requirements: 1) seal from 20°–800°K, 2) be compatible with such fluids as LOX and N_2O_4, 3) require only lightweight flanges, 4) seal axial movements of up to 0.1 in., 5) be reliable, and 6) be easy to assemble correctly.

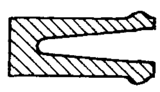
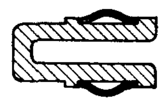
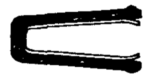
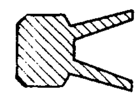
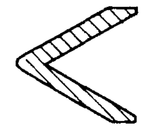
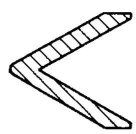
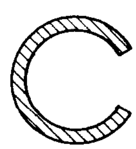
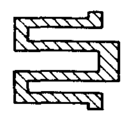
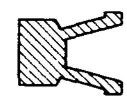
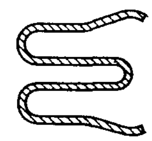
None of the seals discussed earlier will satisfy all of these requirements. Much development work is still being done on the pressure-actuated seals, but the majority of space scientists we have contacted claimed that *with proper design, this principle is superior to all others.* It is best described by examining some of the many designs available commercially which are shown in Table 1. The seal contact area is usually coated with Teflon, silver, or some other material, in a manner similar to that used for the metal O-rings. The backbone is some spring-like metal that will deflect without yielding. A noteworthy feature of these seals is the spring loading due to leg deflection, which will follow quite large flange movements without a drastic reduction in sealing force.

The main disadvantage of this class of seals is that the seal material does not flow sufficiently and therefore may allow small leak paths that would destroy a high vacuum. The danger involved in small (less than 10^{-2} cc/sec) amounts of hydrogen leakage has not been adequately investigated, and leak-rate specifications for hydrogen seals are vague. The double-seal approach with a pumpout or duct line will increase the safety of the seals. Furthermore, they have demonstrated reliability in the field, and with the solution to the problems of cost and small leakage they could very easily become universally accepted for static cryogenic seals.

Temperature-Actuated Seals

There should be agreement that, whenever possible, seal designs should allow the thermal effects to help, rather than

Table 1 Pressure-actuated seals

CROSS SECTION					
TRADE NAME	*NAFLEX*	*PNEUFLEX*	*RACO*	*K SEAL*	*VERTEX*
FEATURES[a]	LONG LEGS, CAPABLE OF MODERATE DEFLECTION.	LONG LEGS. INTEGRAL STOP. CAPABLE OF MODERATE DEFLECTION.	TEFLON BODY WITH INNER METAL SPRING CONTAINMENT REQ'D. FOR HIGH PRESSURE.	SHORT LEGS CAPABLE OF LOW DEFLECTION ONLY.	CAPABLE OF LOW TO MODERATE DEFLECTION.
MANUFACTURER	NAVAN PRODUCTS INC. EL SEGUNDO, CALIF.	DEL MFG. DIV. LOS ANGELES, CALIF.	RACO MFG. CO.	HARRISON MFG. CO. BURBANK, CALIF.	HI-TEMP. RINGS, INC. EL SEGUNDO, CALIF.
COATINGS AVAILABLE	GOLD, INDIUM, COPPER, SILVER, TEFLON.	TEFLON, COPPER, GOLD, SILVER.	NONE	TEFLON, GOLD PLATE WITH FLASH OF TIN, K-6 ALLOY, GOLD PLATE.	TEFLON, SILVER, GOLD.
MINIATURE SEALS AVAILABLE	NO	NO	NO	YES	YES
FLANGE SURFACE FINISH	32 RMS	64 RMS (TEFLON)	64 RMS	8 RMS(MAX.) HIGH VAC. 16 RMS(MAX.)+MET. PL. 32 RMS(MAX.)+TEFLON & "K" ALLOY.	32 RMS
CROSS SECTION					
TRADE NAME	*TETRAFLUOR*	*DELTAU C*	*SKINNER*	*HASKEL*	*DELTAU E*
FEATURES[a]	CAPABLE OF LOW TO MODERATE DEFLECTION	CAPABLE OF LOW DEFLECTION ONLY.	CAPABLE OF HIGH DEFLECTION.	SHORT LEGS CAPABLE OF LOW DEFLECTION ONLY.	CAPABLE OF HIGH DEFLECTION.
MANUFACTURER	TETRAFLUOR INC. INGLEWOOD, CALIF.	PRESSURE SCIENCE, INC. BELTSVILLE, MD.	HYDRODYNE CORP. HOLLYWOOD, CALIF.	HASKEL ENGR. GLENDALE, CALIF.	PRESSURE SCIENCE, INC. BELTSVILLE, MD.
COATINGS AVAILABLE	TEFLON, KEL-F, SILVER, GOLD, TIN, INDIUM, NICKEL.	SILVER, GOLD, TEFLON.	SILVER, GOLD, NICKEL, TEFLON, KEL-F.	SILVER, GOLD, COPPER, SOFT NICKEL, PLATINUM, INDIUM, TEFLON.	SILVER, GOLD, TEFLON.
MINIATURE SEALS AVAILABLE	YES	YES	YES	YES	YES
FLANGE SURFACE FINISH	32-64 RMS	16 RMS - GASES 32 RMS - LIQUIDS	8 RMS	8 RMS. OR BETTER FOR He & HIGH VAC. 16 RMS - GASES 32 RMS - LIQUIDS	16 RMS - GASES 32 RMS - LIQUIDS

[a] All but Raco have metallic bodies with Teflon or metal coatings, and the temperature range is from cryogenic to an upper limit dependent upon the coating

hinder, the seal. The scarcity of temperature-sensitive designs available commercially is surprising, since information concerning the concept shown in Fig. 6a was first published eight years ago and again in the 1961 Cryogenic Engineering Conference.[52, 53] In principle, a low-thermal-expansion metal (invar, for example) is combined with molded rubber to make a seal ring that contracts less below the elastomer's glassy-state transition temperature than does the flange assembly. Thus the sealing force increases as temperature is lowered. The flange design, which allows full contact of the flange faces, helps minimize low-temperature flange movement caused by pressure surges, which would cause leakage.

Another way to apply the temperature-actuated principle is shown in Fig. 6b. Two rings of semicircular cross section are cut so that they form a toroid when placed together. The line of contact is cut diagonally to the plane of the flange faces. For cryogenic applications the outer half of the seal is made of a high-thermal-expansion metal such as aluminum, and the inner half is made of a metal with lower thermal expansion. As the seal cools, the outer half slides against the inner half, increasing the sealing forces. The interface between the halves is coated with Teflon, and the entire seal is encapsulated in Teflon. This seal shows some promise in laboratory tests but has not been field-tested extensively.**

Summary and Conclusions

When flange weight is not a consideration, gaskets of various kinds can be used at cryogenic temperatures. Teflon

** The design is shown with the consent of General Dynamics/Astronautics, which is presently involved in the patent arrangements. The sketch of Fig. 6b does not in any way reflect prior art by the National Bureau of Standards.

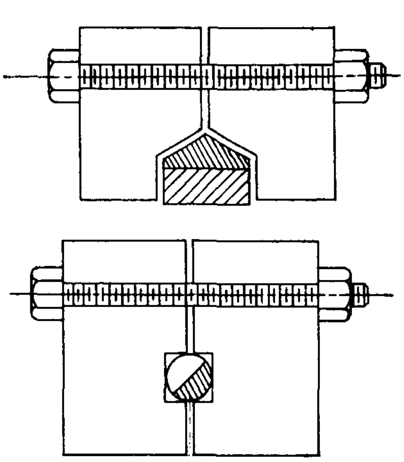


Fig. 6 Temperature-actuated seals.

asbestos composites are used in field applications where small leaks are tolerable, soft metals are used in high-vacuum systems, and hard metals are used in high-pressure systems. Elastomeric O-rings are also used in high-vacuum systems and show some promise in other applications where leak rates must be less than 10^{-4} atm-cc/sec/linear-in. of seal. Metal O-rings coated with Teflon or plated with soft metals can be used in a variety of ways if care is taken to provide polished flange faces.

Pressure-actuated seals are used extensively in designs for which weight is one of the primary considerations, since they require low initial loading and will follow flange deflection. However, the reliability of some of these seals has not been proved in the field, and none has consistently exhibited extremely low leakage requirements needed for high-vacuum applications. Temperature-actuated seals are not used as extensively as the pressure-actuated type, but the principle is sound and should be pursued further. One design has shown field reliability in liquid hydrogen transfer lines.

A well-documented evaluation of all the seals described in this report is needed. This evaluation should include leak-detection capabilities from 100–10^{-7} atm-cc/sec/linear-in. of seal, vibration testing, flange design, and endurance (seal-life) tests. The goal should be to consolidate the many present designs to a few of the best and then to improve on these designs to increase reliability and reduce leakage when necessary.

Another necessity is a definition of "zero" leakage, particularly for liquid hydrogen systems. It is generally accepted that LOX systems can operate with around 0.1–0.3 atm-cc/sec leakage, and high-vacuum systems must show less than 10^{-7} atm-cc/sec. Liquid hydrogen leakage will naturally depend upon the application, but some minimum acceptable value should be available to the seal designer.

LOX compatibility is another area that needs further attention. Many seal systems will never be subjected to the rigid impact requirements set by some agencies, and ambiguous results are reported on some materials, such as Viton and Mylar, when tested by different people.[29,54] Perhaps a more practical test is needed which would be used specifically for seal materials.[55]

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